

5 CLAIMS

What is claimed is:

1. A method for simultaneously determining respective scale factors or
10 alignment angles of sensitive axes in a multi-axis accelerometer device for
measuring acceleration, comprising the steps of:

a) mounting a multi-axis accelerometer device on a turntable in a first
orientation, the turntable having a tilt angle with respect to a vertical axis
defined by a local gravity vector;

b) spinning a multi-axis accelerometer device around an axis of rotation
15 at an angular velocity using the turn table such that the multi-axis
accelerometer device experiences a time varying component of the local
gravity vector;

c) receiving respective outputs of the multiple axis as the multi-axis
20 accelerometer device experiences the time varying component of the local
gravity vector;

d) repeating steps (a), (b) and (c) with the multi-axis accelerometer
device mounted in a second orientation; and,

e) repeating steps (a), (b) and (c) with the multi-axis accelerometer
25 device mounted in a third orientation; and,

f) determining respective scale factors or alignment angles of the
multiple axes of the accelerometer device by combining the respective received
outputs of the accelerometer device with predicted outputs of an ideal
accelerometer, the predicted outputs based on the tilt angle of the turntable,
30 the angular velocity of the ideal accelerometer, and the local gravity vector.

5 2. The method of Claim 1 wherein the angular velocity is constant during the receiving.

 3. The method of Claim 1 wherein the multiple-axis accelerometer device is oriented in three orientations while recording data.

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 4. The method of Claim 1 wherein the time varying components of the local gravity vector are equal to $g \cdot \sin(\theta) \cdot \cos(\phi(t))$ and $g \cdot \sin(\theta) \cdot \sin(\phi(t))$, where θ is the tilt angle, g is the acceleration due to gravity, and ϕ is an angle subtended at the axis of rotation by the accelerometer and the component of gravity in the plane of rotation of the accelerometer.

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 5. The method of Claim 1 further including the step of filtering the outputs of the multiple axis using respective low pass filters.

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 6. The method of Claim 5 further including the step of sampling the low pass filtered outputs of the multiple axis using respective analog to digital converters.

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 7. The method of Claim 6 further including the step of receiving the sampled outputs of the multiple axis and combining the sampled received outputs of the multiple axis with one or more predicted outputs to determine the scale factors of the sensitive axes.

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 8. The method of Claim 6 further including the step of receiving the sampled outputs of the multiple axis and combining the sampled received

5 outputs of the multiple axis with one or more predicted outputs to determine the alignment angles of the sensitive axes.

9. The method of Claim 1 further including the steps of:

10 taking respective Fourier transforms of the received outputs of the multiple axis;

taking the Fourier transform of the predicted outputs of an ideal accelerometer; and

15 combining the respective Fourier transforms of the received outputs and the predicted output to determine the scale factors or alignment angles of the multiple axis of the multi-axis accelerometer device.

10. A system for simultaneously determining respective scale factors or alignment angles of a multi-axis accelerometer device for measuring acceleration, comprising:

20 a turn table mechanism configured to mount an accelerometer device having multiple axis for calibration, the turntable having a tilt angle with respect to a vertical axis defined by a local gravity vector, the turntable configured to spin the accelerometer device around an axis of rotation at an angular velocity such that the accelerometer device experiences time varying components of the local gravity vector; and

25 a processor system coupled to receive respective outputs of the multiple sensitive axes of the accelerometer device, the processor system configured to record the outputs of the accelerometer device as the device experiences the time varying components of the local gravity vector and to determine
30 respective scale factors or alignment angles of the multiple axis of the accelerometer device by combining the logged outputs of the accelerometer

5 device with a predicted output of an ideal accelerometer, the predicted output
based on the tilt angle of the turntable, the angular velocity of the ideal
accelerometer and the local gravity vector.

10 11. The system of Claim 10 wherein the turntable is configured to
maintain a constant angular velocity during the recording.

15 12. The system of Claim 10 wherein the time varying components of
the local gravity vector are equal to $g \cdot \sin(\theta) \cdot \cos(\phi(t))$ and $g \cdot \sin(\theta) \cdot \sin(\phi(t))$,
where θ is the tilt angle, g is the acceleration due to gravity, and ϕ is an angle
subtended at the axis of rotation by the accelerometer and the component of
gravity in the plane of rotation of the accelerometer device.

20 13. The system of Claim 10 further including a low pass filter for
filtering the outputs of the accelerometer device.

25 14. The system of Claim 13 further including an analog to digital
converter for sampling the low pass filtered outputs of the accelerometer
device.

30 15. The system of Claim 14, wherein the processor system is further
configured to determine the scale factors or alignment angles of the
accelerometer device by recording the sampled outputs of the accelerometer
device, and by combining the sampled, recorded outputs of the accelerometer
device with the predicted output of an ideal accelerometer.

5 16. The system of Claim 15 wherein the processor system is further configured to determine the scale factors and/or alignment angles of the accelerometer device by:

taking respective Fourier transforms of the recorded outputs of the multiple sensitive axes;

10 taking the Fourier transform of the predicted outputs of an ideal accelerometer; and

combining the respective Fourier transforms of the recorded outputs and the predicted output to determine the scale factors or alignment angles of the multiple sensitive axes of the multi-axis accelerometer device.

15 17. A method for simultaneously determining respective scale factors or alignment angles of sensitive axes in a multi-axis accelerometer device for measuring acceleration, comprising the steps of:

20 a) mounting a multi-axis accelerometer device on a turntable in a first orientation, the turntable having a tilt angle with respect to a vertical axis defined by a local gravity vector;

25 b) spinning a multi-axis accelerometer device around an axis of rotation at an angular velocity using the turn table such that the multi-axis accelerometer device experiences a time varying component of the local gravity vector;

c) receiving respective outputs of the multiple axis as the multi-axis accelerometer device experiences the time varying component of the local gravity vector;

30 d) determining respective scale factors or alignment angles of the multiple axes of the accelerometer device by combining the respective received outputs of the accelerometer device with predicted outputs of an ideal

5 accelerometer, the predicted outputs based on the tilt angle of the turntable,
the angular velocity of the ideal accelerometer, and the local gravity vector.

10 18. The method of Claim 17 further including the step of repeating steps
(a), (b) and (c) with the multi-axis accelerometer device mounted in a second
orientation.

15 19. The method of Claim 18 further including the step of repeating steps
(a), (b) and (c) with the multi-axis accelerometer device mounted in a third
orientation.

This appendix shows a solution method for the system of equations derived in the main body of the patent, to obtain the scale factors and the alignment vectors of the sensitive axes of the multi-axis accelerometer device.

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In Orientation 1:

$$P_{A,1} = \kappa * \alpha_A * g * \sin(\theta) * \exp(i * \phi_1) * (A_x - i * A_y) \quad (1)$$

$$P_{B,1} = \kappa * \alpha_B * g * \sin(\theta) * \exp(i * \phi_1) * (B_x - i * B_y) \quad (2)$$

$$P_{C,1} = \kappa * \alpha_C * g * \sin(\theta) * \exp(i * \phi_1) * (C_x - i * C_y) \quad (3)$$

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In Orientation 2:

$$P_{A,2} = \kappa * \alpha_A * g * \sin(\theta) * \exp(i * \phi_2) * (A_x + i * A_y) \quad (4)$$

$$P_{B,2} = \kappa * \alpha_B * g * \sin(\theta) * \exp(i * \phi_2) * (B_x + i * B_y) \quad (5)$$

$$P_{C,2} = \kappa * \alpha_C * g * \sin(\theta) * \exp(i * \phi_2) * (C_x + i * C_y) \quad (6)$$

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In Orientation 3:

$$P_{A,3} = \kappa * \alpha_A * g * \sin(\theta) * \exp(i * \phi_3) * (A_x + i * A_y) \quad (7)$$

$$P_{B,3} = \kappa * \alpha_B * g * \sin(\theta) * \exp(i * \phi_3) * (B_x + i * B_y) \quad (8)$$

$$P_{C,3} = \kappa * \alpha_C * g * \sin(\theta) * \exp(i * \phi_3) * (C_x + i * C_y) \quad (9)$$

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Ideal Accelerometer with sensitive axis parallel to the plane of rotation:

$$P_{\text{nominal}} = \kappa * \alpha_{\text{nominal}} * g_{\text{nominal}} * \sin(\theta_{\text{measured}}) \quad (10)$$

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Additionally, the peak DFT values are known from the recorded data and generated ideal data.

- 5 In the initial stage, the value of κ can be determined from equation (10), by substituting the known values for P_{nominal} , α_{nominal} , g_{nominal} and θ_{measured} .

In the next stage, the absolute value of α_A is calculated. This is the scale factor

- 10 of accelerometer A. By squaring (1), the following equation is obtained:

$$|P_{A,1}|^2 = |\kappa|^{2*}(\alpha_A * g * \sin(\theta))^2 * |\exp(i*\phi_1)|^2 * |(A_x - i*A_y)|^2 \quad (11)$$

$$\therefore |P_{A,1}|^2 = |\kappa|^{2*}(\alpha_A * g * \sin(\theta))^2 * \{(A_x)^2 + (A_y)^2\} \quad (12)$$

Similarly, by squaring (4):

$$|P_{A,2}|^2 = |\kappa|^{2*}(\alpha_A * g * \sin(\theta))^2 * \{(A_x)^2 + (A_z)^2\} \quad (13)$$

- 15 Also, by squaring (7):

$$|P_{A,3}|^2 = |\kappa|^{2*}(\alpha_A * g * \sin(\theta))^2 * \{(A_z)^2 + (A_y)^2\} \quad (14)$$

Adding (12), (13) and (14) gives

$$\begin{aligned} & |P_{A,1}|^2 + |P_{A,2}|^2 + |P_{A,3}|^2 = \\ 20 & |\kappa|^{2*}(\alpha_A * g * \sin(\theta))^2 * \{(A_x)^2 + (A_y)^2 + (A_x)^2 + (A_z)^2 + (A_z)^2 + (A_y)^2\} \end{aligned} \quad (15)$$

However, since A_x , A_y , and A_z form an alignment vector $[A_x, A_y, A_z]$, which is a unit vector, the following identity holds:

$$[A_x, A_y, A_z] \cdot [A_x, A_y, A_z] = 1 \quad (16)$$

- 25 This yields the identity

$$(A_x)^2 + (A_y)^2 + (A_z)^2 = 1 \quad (17)$$

Substituting (17) into (15) gives

$$|P_{A,1}|^2 + |P_{A,2}|^2 + |P_{A,3}|^2 = |\kappa|^{2*}(\alpha_A * g * \sin(\theta))^2 * \{2\} \quad (18)$$

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- 5 The value α_A can be obtained by substituting the values for $P_{A,1}$, $P_{A,2}$, $P_{A,3}$, and θ , as well as the value for κ from solving (10), into equation (18) and solving the equation (18) with the knowledge that α_A is positive.

The scale factors of accelerometer B and accelerometer C, which are α_B and α_C respectively, can be obtained in a similar manner. Thereby, the scale factors of the sensitive axes of the multi-axis accelerometer device are obtained.

In the final stage the alignment vectors are computed.

Dividing (1) by (2) and rearranging gives:

$$15 \quad P_{A,1} * \alpha_B * (B_x - i * B_y) - P_{B,1} * \alpha_A * (A_x - i * A_y) = 0 \quad (19)$$

Similarly dividing (2) by (3) and rearranging gives:

$$P_{B,1} * \alpha_C * (C_x - i * C_y) - P_{C,1} * \alpha_B * (B_x - i * B_y) = 0 \quad (20)$$

Dividing (4) by (5) and rearranging gives:

$$20 \quad P_{A,2} * \alpha_B * (B_x + i * B_z) - P_{B,2} * \alpha_A * (A_x + i * A_z) = 0 \quad (21)$$

Similarly dividing (5) by (6) and rearranging gives:

$$P_{B,2} * \alpha_C * (C_x + i * C_z) - P_{C,2} * \alpha_B * (B_x + i * B_z) = 0 \quad (22)$$

Dividing (7) by (8) and rearranging gives:

$$25 \quad P_{A,3} * \alpha_B * (B_z + i * B_y) - P_{B,3} * \alpha_A * (A_z + i * A_y) = 0 \quad (23)$$

Similarly dividing (5) by (6) and rearranging gives:

$$P_{B,3} * \alpha_C * (C_x + i * C_z) - P_{C,3} * \alpha_B * (B_x + i * B_z) = 0 \quad (24)$$

Additionally, $[A_x, A_y, A_z]$, $[B_x, B_y, B_z]$ and $[C_x, C_y, C_z]$ are unit vectors. Rearranging (17) gives the following equation:

$$30 \quad (A_x)^2 + (A_y)^2 + (A_z)^2 - 1 = 0 \quad (25)$$

Similarly, the following equations can be derived:

$$(B_x)^2 + (B_y)^2 + (B_z)^2 - 1 = 0 \quad (26)$$

$$(C_x)^2 + (C_y)^2 + (C_z)^2 - 1 = 0 \quad (27)$$

- 10 The set of equations, (19) through (27), can be solved for the alignment vectors, $[A_x, A_y, A_z]$, $[B_x, B_y, B_z]$ and $[C_x, C_y, C_z]$, using a multidimensional Newton-Raphson solution method. The nominal values of the alignment vectors can be used as initial values for the Newton-Raphson method.

- 15 Thus, the values of the scale factors and the alignment vectors of the sensitive axes of the multi-axis accelerometer device can be obtained.